Discussion of Tevatron Fixed Target Options after Run II

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Abstract

Following the very successful completion of Run II in the upcoming years, the Tevatron synchrotron will become available for other uses. Assuming that its function as a proton-antiproton collider is no longer supported, several new (and old) options become available. In this report we examine specifically two scenarios, namely the use of the accelerator as a "stretcher ring" for 120-150 GeV fixed target operation to the existing SY120 facilities, or possibly as a high energy (800 GeV) fixed target synchrotron for neutrino experiments. While much more work needs to be done to understand fully the implications of using the Tevatron in these modes, here we attempt to present the major factors which may influence the decisions necessary for going forward with either of these options. Other options, for example the use of the tunnel for electron storage ring or damping ring studies, will be left to other reports.

Until 2000 the Tevatron operated as both a fixed target synchrotron and a colliding beams accelerator and storage ring during the course of its normal operation. As the first superconducting synchrotron in the world, it was able to deliver fixed target beams at nearly twice the particle energy of any other fixed target facility. While other high energy superconducting accelerators have been built since (HERA, RHIC, and the soon to be completed LHC), none of these newer accelerators possess the ability to rapidly ramp to full field and thus support a viable fixed target program. Although the fixed target operation was halted in 2000, the Tevatron remains the only accelerator capable of producing quality fixed target beams in the $\sim$1 TeV energy range (800 GeV being the nominal high energy limit).

A major feature of the the Main Injector project was to introduce a 120 GeV fixed target operation for "test beams," which at the time was envisioned to support the on-going development of detector components for the SSC and other future experimental facilities, and for other physics experiments which may be carried out in this energy range. This operation, also dubbed "Switch-yard 120," came on-line in 2004 and has carried out several short experimental programs during the past several years. At present, SY120 reflects a small impact on other operations, mainly generated by interruptions in the facility time line for special 120 GeV Main Injector ramps for this purpose. On the other hand, one also could say that beam time to the SY120 program has been limited due to the fact that it interrupts the other higher-priority programs at the lab, namely the production of antiprotons and the delivery of high intensity proton beams to the NuMI operation. The present amount of beam delivery is small, providing $\sim 1 \times 10^{12}$ protons (1 Tp) over a 4 sec. flat-top, every

2 minutes for an instantaneous rate of about 250 Gp/sec, or an average rate of 8 Gp/sec, with a low duty factor of only $4/120 = 3.3\%$. But the demand for test beams may be greater than the present level, especially in light of the needs for NOνA, MINERνA, and increasing interest in test beams for the International Linear Collider effort. Additionally, there may be other experimental applications with high energy fixed target beams, such as rare Kaon decay physics, where Fermilab offers essentially the only viable alternative.

Below we discuss briefly the use of the Tevatron in two different modes. The first mode is in support of the existing SY120 program. The second is the resurrection of the 800 GeV fixed target operation. The latter would be more disruptive to the present neutrino program, as more cycles would need to be taken from the time line to fill the Tevatron. For SY120, beam can be sent to the Tevatron and slow-spilled over many minutes, with very little interruption to other operations. This option also would be easier to implement in short order, as most components are already in place. At the end of this document, a list of possible beam (and paper) studies are presented that could be performed in order to help further assess the viability of each option.

1 Tevatron 120/150 GeV Fixed Target Operation

It is conceivable that the Tevatron could be used very readily as a "stretcher ring" for 120-150 GeV Fixed Target operation to the existing Fermilab Switchyard. (These two choices of energy are used since the Main Injector operates routinely at both levels.) For example, one could imagine extracting beam from the Main Injector on two pulses separated by $\sim$1.5 sec, filling the Tevatron with beam, and during the next several minutes performing resonant extraction from the Tevatron toward the existing 120 GeV Switchyard. In this case the Tevatron would be re-tuned to operate DC at this slightly lower energy. To achieve the same average spill rate as in current SY120 operation, consider filling the Tevatron with 30 Tp from the Main Injector every 60 min. This could provide our average spill rate of 8 Gp/sec to the Switchyard. However, rather than providing beam with today's 3.33% duty factor, the Tevatron would deliver particles with a 99.9% duty factor, and with essentially no impact on the neutrino program. Additionally, there would be extra flexibility in the test beam program. A fraction of the beam circulating in the Tevatron can be extracted "on demand" for short durations, at variable instantaneous spill rates, for example. It also may be possible to operate the Tevatron at slightly lower fields to vary the primary beam energy to the Switchyard. On the other hand, one could also consider pushing the SY120 beam lines to handle 150 GeV beam, thus operating the Tevatron at its present injection energy. The beam line magnets are capable of this, though some power supplies may need to be upgraded for higher currents. For what follows we will assume 120 GeV operation, but most comments are equally valid for 150 GeV operation as well.

1.1 Accelerator Intensity Challenges

The Tevatron intensity used in the example above, 30 Tp per pulse, was chosen as this was essentially the record intensity achieved in the Tevatron during its fixed target history. However, during the earlier running the intensity was mainly limited by beam instabilities at high energy. Today, the Main Injector is capable of providing greater than 40 Tp per pulse, which could, in principle, fill the Tevatron to 80 Tp. The existing internal abort system should be able to handle the 120 GeV conditions at this level, to the extent that we equate 80 Tp @ 120 GeV with 10 Tp @ 980 GeV, which is today's Tevatron Run II conditions. (Naturally, fault conditions, *etc.*, would need to be verified.) However, rather than extrapolate to 2.5 times previous operational intensities, we will assume for now a modest increase to 40 Tp per pulse at 120 GeV and acknowledge that intensities beyond this may be possible.

1.2 Slow Resonant Extraction System

Hardware – Beam transfered today to SY120 from the Main Injector passes through the Tevatron Injection Lambertson Magnet. For today's SY120 operation, this magnet is left off, and the beam passes straight through and up into the SY120 beam line. In order to extract beam from the Tevatron this magnet needs to be turned on with its polarity reversed with respect to its 150 GeV injection setting. An electrostatic septum would kick the resonant particles into the field region of this same magnetic septum and direct them up toward the SY120 beam line. There would be a small hit in duty cycle as the current and polarity of this Lambertson magnet would need to be changed before and after the injection process.

The natural place for the electrostatic septum, assuming half-integer resonant extraction, would be the C0 straight section, which currently consists mostly of free space. To better facilitate slow spill, the optics of the C0 straight section could be replaced with the old "high-beta" Collins quads configuration used in the D0 straight section during previous fixed target runs. (One could, perhaps, contemplate a similar optical arrangement at F0.) The colliding beams detector regions would be de-tuned, or perhaps replaced with standard long straight section optics as well.

The other piece of hardware required is the resurrection of the slow-spill feedback system, referred to as QXR, which consists of fast air-core quadrupoles and their associated power supplies and electronics. Though most of the QXR system still exists, one would likely wish to upgrade much of the electronics and controls. Since the number of components to this system is small this would be a relatively low cost upgrade.

Beam Dynamics – A more detailed look at the available phase space at 120-150 GeV for slow resonant extraction to take place will need to be undertaken. The Tevatron performed well at 800 GeV, but the beam is at least 2.5 times larger at 120 GeV. On the other hand, slow resonant extraction is routinely performed at 120 GeV from the Main Injector. The larger amplitude functions in the Tevatron should help with the step size across the septa. It should also be pointed out that slow spill was first established in the Tevatron at an energy of 400 GeV, in 1983, so performance at a lower energy has been demonstrated.

1.3 Other Considerations

Since there will be no ramping of the Tevatron, then effects such as "snap-back," tune and chromaticity drift, etc., will be of little consequence, and the quench margin will be much higher. With no ramping, the magnet system should be very reliable. It is possible to employ barrier bucket RF technology, at a very modest cost, to contain the beam yet provide an abort gap, and to provide "debunched" beam to the experiment(s). Beam could be compressed and prepared for extraction with the barrier bucket system during the time that the Lambertson magnet switches polarity. The implications of such a system on beam instrumentation would need to be examined.

The main drawback of this scenario which immediately comes to anyone's mind is the operating cost of the cryogenic system and of the supporting infrastructure for the four-mile ring to support a 120 GeV fixed target program. The cost of running the Tevatron today is estimated at approximately $25-30M/year, for year-round operation minus a 1-2 month shutdown. Unfortunately, the fact that the power use of the Tevatron cryogenics system is dominated by the heat leak inherent in the magnets and in high temperature power leads, and the fact that the two-phase helium system cannot function above about 5°K prevent any savings from operating at a higher temperature with the present cryo equipment. However, power losses due to ramping will be avoided. Corrector currents, which also produce a significant source of heat leak through their power leads, will be running at much reduced currents. Reduced demands on the RF system will also help the operational costs. The main advantage of this program would be that it could easily come on line with very little additional up-front costs and with very little interruption to other laboratory operations. Since this proposal uses mostly already-existing equipment, initiating this program should be rather inexpensive.

Above we looked at parameters to provide similar average particle delivery rates as the present SY120 program, but with vastly improved duty factor. However, suppose that the time between Tevatron fills is shortened to provide two 20 Tp fills from the Main Injector every 10 minutes. Then the SY120 program could operate with an average spill rate of 66 Gp/sec with a 99.5% duty factor, and with a 0.5% hit on the Main Injector neutrino program (assuming a 1.4 sec cycle time). Up the rate to a fill every minute, and one gets nearly 700 Gp/sec with a 95% duty factor, and 5% hit on the neutrino program, *etc.* Additionally, further increases in the Tevatron beam intensity may still be feasible.

As a final example for this section, let's assume the Tevatron can absorb the full 50 Tp intensity of the Main Injector in a single-turn transfer. Barrier buckets are employed to contain the beam and following debunching – and after a polarity change of the injection/extraction Lambertson magnet – slow spill is performed. Suppose one 1.4 sec cycle is taken every 14 seconds in the time line for injection into the Tevatron, and that the spill lasts for 11 seconds. This operation would be a $1.4/14 = 10\%$ hit on the NuMI operation, would provide an average spill to the switchyard of 3.6 Tp/sec, a maximum instantaneous spill rate of about 4.5 Tp/sec, (duty factor of approximately 78%), and thus would deliver about 7×10^{19} POT/year assuming beam is received 66% of an entire year.

2 Tevatron 800 GeV Fixed Target Operation

We now examine the use of the Tevatron as a high energy fixed target synchrotron. Previous 800 GeV fixed target operation of the Tevatron ran with a maximum throughput of roughly 25-

28 Tp per pulse every 60 sec with a duty cycle of roughly 33-40%.[1] This beam was typically split, over a 20-23 sec flat-top period, between experiments that required slow resonantly extracted beam and neutrino experiments requiring fast extracted beams. To meet the demands of today's proposed neutrino experiments, the facility needs to be able to deliver approximately 1.5×10^{20} protons on target over a few years of running.[2] Consider four years of running, at 66% overall operation efficiency per year. This translates to an average particle delivery rate during running of 1.8 Tp/sec. Suppose further that, for the neutrino experiment, the 60 second ramp can be trimmed to 40 seconds (eliminating the need for a long flat-top for slow spill). Then, each pulse from the Tevatron would need to have intensity of about 75 Tp, more than 2.5 times the previous record intensity. The subsections below address some of the major issues regarding re-institution of a Tevatron fixed target program, and issues associated with meeting the above intensity demand.

2.1 Energy and Ramp Rate

The original Tevatron fixed target program ran at 800 GeV, and stress and strain on the superconducting magnets was a major issue. For some neutrino experiments, beam power is the major figure of merit, and so operating the Tevatron at a lower energy, and correspondingly shorter cycle time, would produce similar beam power. As the forces on the conductors go like B^2, the stress and strain on the magnets would be reduced. However, the recent experimental proposal referred to above relies upon a particular production threshold requirement, which constrains the energy to be well above 500 GeV. With this in mind, we will assume 800 GeV operation, consistent with prior history, and note that lower energies and shorter cycle times are always possible.

Ramp rate studies of Tevatron dipole magnets have been performed, and rates of 200-300 A/sec can be maintained at 4.6° K without quenching.[3] While ramp rates this high are not used during Collider operation, the power supply system in principle could still perform at this level. To increase reliability, however, some PS system components may need to be upgraded. Note that a ramp rate of 220 A/sec is equivalent to an acceleration rate of about 50 GeV/sec. This rate, with "end effects," would give a total cycle time of about 40 sec. The maximum ramp rate used in the last Tevatron fixed target run was 55 GeV/sec.

The Tevatron RF system contains eight 53 Mhz cavities. This system has been used for collider mode as well as for fixed target mode. Each cavity is capable of $\sim$360 kV and, if reconfigured back to the previous fixed target state,the 8 cavities would generate about 3 MV. This yields a maximum acceleration rate of, $f_0 eV \sin(\phi_s) = 47.7 \times 10^3/\text{sec} \cdot 3\ \text{MeV} \cdot (1/2) = 70$ GeV/sec, consistent with our ramping requirements above. Beam loading effects and appropriate compensation will need to be addressed for the anticipated higher intensity operation.

With these considerations, it is envisioned that a neutrino fixed target experiment could be performed by ramping up and down at a rate consistent with the above parameters, and with a 1 sec flat-top during which a series of short bursts of beam ("pings") would be extracted using fast resonant extraction, yielding about a 40 second cycle time. Slightly shorter cycle times may be

[1] August 1997. J. Crawford, FNAL, private communication.

[2] J. Conrad and P. Fisher, "A Proposal for a High Precision Neutrino Scattering Experiment at the Tevatron," May 30, 2007, submitted to FNAL Steering Committee.

[3] Fermilab internal report MTF-93-0010.

possible without further upgrades, but only by about 5-10%.

2.2 Comments on High intensity

The record intensity extracted from the Tevatron in a cycle at 800 GeV was almost 30 Tp, in 1997, though 20-25 Tp was far more typical. At that time, the bunch length during acceleration would shrink to the point where the accelerator impedance would generate a transverse instability at higher energies (∼600 GeV), resulting in aborts and sometimes quenches. This was compensated as best as possible with "bunch spreading" techniques (blowing up the emittance via RF noise sources). Since those years, many improvements to the Tevatron beam impedance have been made during Run II, including, for example, reduction of the Lambertson magnet transverse impedances which were identified as major sources. Additionally, advances in RF techniques/technology and damper systems, *etc.*, may allow, with enough studies and money, much better compensation of these effects, if required. This is a primary R&D point, if intensities near 75 Tp are ever to be realized in the Tevatron.

2.3 Re-commissioning of Extraction System

While the 120 GeV program discussed in Section 1 would extract beam at the F0 straight section through the existing injection Lambertson magnet, half of the F0 straight section is used for RF acceleration. Extraction of 800 GeV beam requires a longer straight section than for 120 GeV beam, and thus F0 would be insufficient. One may consider other straight sections, depending upon the ultimate placement of an experiment, but the most straightforward and obvious option would be to re-install the previously used extraction channel in the A0 straight section and transport beam to the existing Switchyard area from there. This equipment is currently in storage and available for use.

Additionally, the resonant extraction magnet system ("QXR") is also required, just as in the 120 GeV scenario. This system employed fast air-core quadrupoles installed at warm straight sections in the Tevatron for fast feedback/feedforward tune adjustment during the resonant extraction process. Again, this equipment mostly still exists, but both hardware and software need to be re-commissioned, though it may be desirable to update some electronic components.

The neutrino experiment being discussed has requested "pinged" beam, which is a short burst of particles brought about by the QXR system. In the past, *pings* were generated a few times over the course of a 20 sec flat-top, separated by several seconds, to send beam to neutrino experiments. The new experiment will likely require tens of *pings* per cycle, during an assumed 1 sec flat-top. Fifty pulses, for example, of few millisecond duration during a one second flat-top at first glance appears feasible. *Pinging* without slow spill going on in the background may require new extraction regulation techniques, though should be feasible.

It must be pointed out that, even with stable beam at 800 GeV, the slow and fast resonant extraction processes are inherently lossy, on the scale of 1-2%, determined by the step size across the thin electrostatic septum wires. With between 20-30 Tp extracted over 20 seconds, the loss rates were tolerable. Extracting 2.5 times this amount in 1/20-*th* the amount of time without quenching the Tevatron will need further study. While this may be totally feasible, alternative methods for fast extraction could be contemplated. For instance, if an appropriate RF bunching scheme can be employed to prepare bunches spaced by 400 nsec or so, then a fast kicker magnet system might be able to extract 50 such bunches one-by-one to the switchyard. This would be a much cleaner extraction than the inherently-lossy resonant extraction process. (Note that NuMI, another high intensity program, resorted to kicked extraction as opposed to resonant extraction for this reason.) Spreading the beam across fewer, longer bunches may also help to mitigate coherent instability issues. This opens up another possible R&D point to pursue.

As an historical aside, the highest intensity extracted in a single pulse (*i.e.*, not during a slow spill) without quenching the Tevatron was about 10 Tp.[4] (Also, this was a test, not a normal operational procedure.) To set the scale, extracting 75 Tp in 50 *pings* would give 1.5 Tp/*ping*. One could consider, if viable for the experiment, other scenarios like six 8 Tp *pings*, should this make a kicker system more conducive operationally, and if the Tevatron can handle this operation without quenching.

The exact method used for 800 GeV operation would be a point closely negotiated between the laboratory and the experiment(s) using the beam. Both resonant extraction and kicker methods should be feasible within reasonable constraints.

2.4 Tevatron abort system

The abort system used during high intensity fixed target operation was located at C0 and was capable of delivering 1 TeV proton beams at 30 Tp, repeatedly every "several" seconds, to the abort dump. While not used in Collider operation, this beam dump and beam delivery equipment near the C0 straight section is still available and still accessible, if the extraction devices were to be re-installed.

Part of the beam abort system design included "C" magnets that were tied in with the Tevatron power system in order to ramp directly with the Tevatron main magnet bus. During Run II, several of these magnets were replaced with Main Injector-style dipole magnets to improve the vertical aperture for the helical orbit manipulations in this region. The old abort magnets would need to be reinstalled, or else a new configuration considered.

The ultimate parameters of the neutrino experiment being discussed pushes the beam stored energy from about 3.5 MJ (27 Tp at 800 GeV) toward 10 MJ. The design limits of this system would need to be re-examined, and the implications and environmental impact of re-establishing this area as the primary abort must be looked at carefully.

[4] G. Annala, FNAL, private communication.

2.5 Magnet Stress and Strain

A big issue during early 800 GeV fixed target operation was the reliability of the Tevatron dipole magnets. Failures are much more likely to occur – and did occur – due to stresses produced over and over again during the ramping of the magnets. Well into the Tevatron program, after many failures, issues with lead restraints within the cryostat were identified and all dipole magnets were repaired in the tunnel. Since that time, the Tevatron has been able to average over 250,000 cycles between failures of dipole magnets.[5] Note that a neutrino program which demands 1.5×10^{20} POT, using a synchrotron that delivers 75 Tp every cycle, requires 2 million cycles – thus, on the order of 8 failures could be expected during the course of the experiment.

Once the fixed target operation was halted, and only Collider operation was foreseen, the capability to repair and rebuild Tevatron magnets was greatly reduced at the laboratory. Either these capabilities would need to be re-established at the laboratory, or the number of spare Tevatron magnets will need to be factored in when discussing possible number of years of operation. Further steps that can be taken to make the operation of the magnets more robust should be carefully examined. Additionally, when discussing accelerator availability, downtime due to magnet failures (which take days to repair) need to be considered.

3 Summary

From the point of view of hardware implementation, it should be straightforward to establish a 120-150 GeV fixed-energy Tevatron operation for providing beam to the existing SY120 facility. Modest funds would be required to install and re-commission the resonant extraction system, and a barrier bucket RF system may be desirable. The work that needs to be performed in the near future is to verify that the available magnet aperture, field quality, and slow resonant extraction equipment can conspire to produce efficient slow spill at these lower energies for today's typical beam properties (emittance and momentum spread).

Greater issues appear with 800 GeV operation for neutrino physics, most notably the remediation of beam instabilities at high intensity in the Tevatron, and perhaps magnet reliability (and availability of spares). High intensity operation likely will require further improvements to the impedance of the Tevatron, and/or new beam damping techniques to control beam instabilities and perhaps beam loading compensation. Further negotiations with proposed experiments will lead to the choice of an appropriate extraction technique that can handle the high beam intensities required.

Both options require extensive operating funds to operate the Tevatron. Maintaining the synchrotron at a lower energy without excessive ramping will be less expensive, but since most of the power will be in refrigeration, the cost difference will be relatively small. However, the lower-energy option is certainly easier and less costly to implement immediately and so this course could be started soon after Run II. Time could then be spent preparing for future 800 GeV fixed target operation at a later date if desired.

[5] *ibid.* This "rate" includes failures of Collider-specific magnets, such as low-beta quadrupoles.

Below lists are provided of further studies that should be performed, both experimentally and computationally, to further explore the 120-150 GeV and 800 GeV operation of the Tevatron in fixed target mode, as well as summary tables of parameters and approximate costs of implementation and operation.

Many helpful comments, input and discussion from Jerry Annala, Mike Church, Dave Finley, Cheng-Yang Tan, John Crawford, Dan Wolff, and Don Edwards are greatly appreciated.

3.1 Further Courses of Study

Accelerator Studies to Consider:

1. Verify 55 GeV/sec ramp rate with present Tev mag/PS system
2. Tevatron impedance measurements
3. Beam instability limit exploration @ high energy
4. Aperture and corresponding beam lifetime @ 120-150 GeV, and @ high intensity
5. Possible bunch preparation studies in MI (for 800 GeV operations)

Paper Studies to Consider:

1. Slow extraction system requirements using F0 extraction point (120/150)
   mag protection, septum thickness, loss points, etc.
2. Fast extraction system requirements using A0 extraction point (800)
   same as above; also, techniques for many (50) extractions over 1 sec
3. Impedance Budget / Instabilities analysis of Tevatron (all energies)
4. Damping system requirements document (all energies)
5. RF upgrades for hi-intensity TeV operations — beam loading compensation
6. Debunching and/or other RF gymnastics to meet experimental demands
7. Optics Optimization for 120 GeV and 800 GeV FT operation
   as well as aperture mitigation for new operation
8. Requirements of upgrading SY120 beam line to SY150
9. Instrumentation upgrades/requirements
10. Kicker magnet upgrades/requirements
11. Operational cost models — PS + cryo + ...
12. Hardware inventory – magnets, cables, power supplies, *etc.* for all options

3.2 Summary Tables

Table 1: Parameter Comparison for Tevatron Fixed Target Options. Maximum intensities of 50 Tp/pulse are used for scaling purposes.

	low energy	high energy	
Proton energy	150	800	GeV
Operational Mode	DC	AC	
MI cycle time	1.4	1.4	sec
TEV cycle time	14-3600	36-40	sec
Spill Duty Factor	85-99.9	—	%
MI intensity	15-50	50	Tp
TEV intensity	30-50	50	Tp
Fast Pulses	—	1-50/cycle	
Extr. Method	Res. Extr.	Res. Extr./Kicker	
Spill rate (ave)	0.01-3.5 (var)	1.4	Tp/sec
Spill rate (inst)	0.01-4.5 Tp/sec (var)	$\sim$1 Tp/400 nsec	
Ramp rate (max)	0	55	GeV/sec
# Tev cycles/year	few	0.5×10^6	
Stored energy (50 Tp)	1.2	6.4	MJ
POT/yr (max, 50 Tp/fill)	7	3	10^{19}
Abort location	A0	C0	
Electrostatic Septum location	C0	D0	
Extraction Channel location	F0	A0	

Table 2: Very Rough Cost Estimates of Major Systems (M&S only)

	120-150 GeV		800 GeV	
	Implement ($K)	Ops ($K/yr)	Implement ($K)	Ops ($K/yr)
Magnet Power System		250		1400
– dump switch upgrade	—	—	135	—
– B48 abort pulsers	—	—	500	—
Cryogenics				
– power	—	12000	—	12000
– cryogens	—	3200	—	3200
RF				
– 53 MHz	—	400	—	400
– barrier bucket	500		—	
Other				
– SY (@ 150, 800 GeV)*	200	800	—	800
– Kickers, dampers, *etc.*	?	—	?	—
– Instrumentation	?	—	—	—
– *Experiments*	?	?	?	?

*Assumes ***NOT*** using cryogenic Left/Right Bends for particle transport.

One "year" = 10 mos. running, 2 mos. shutdown.

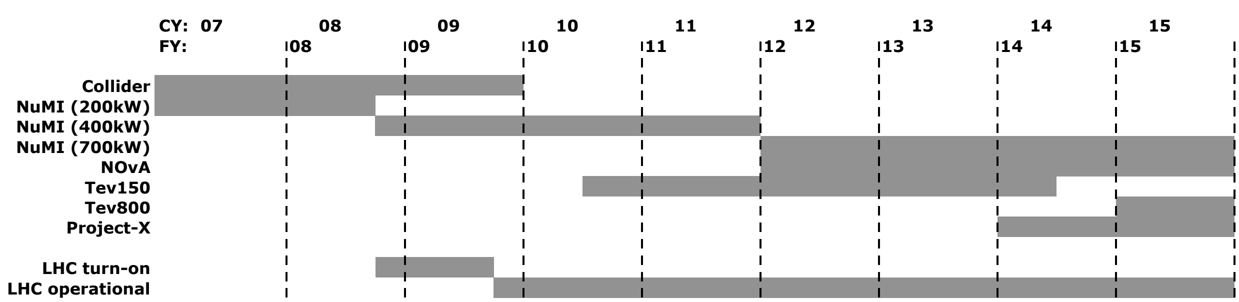

Figure 1: Possible Calendar of Events